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15 Gb/s OFDM-based VLC using Direct Modulation of 450 nm GaN Laser Diode

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ABSTRACT

A record data rate for visible light communications (VLC) using a transistor outline (TO) packaged Gallium Nitride (GaN) laser diode is reported. Using a system 3 dB bandwidth of 1.4 GHz data transmission at 15 Gb/s is reported. This is achieved due to the use of orthogonal frequency division multiplexing (OFDM) in combination with a high system signal to noise ratio (SNR) and adaptive bit loading extending the effective bandwidth to 2.5 GHz. To the best of authors knowledge this is the highest reported data rate for single channel VLC.

Keywords: Optical Communications, Visible Light Communications, Digital Communications

1. INTRODUCTION

GaN-based semiconductors are a safe and efficient means of modernizing our existing lighting infrastructure and could reduce lighting energy requirements to 1/5 of their current consumption.[1] The prospective ubiquity of GaN based lighting has given rise to research into using VLC as the data demand grows on the already congested radio frequency (RF) spectrum.[2] GaN based lighting devices are of interest due to their high speed modulation capabilities and in tandem with OFDM light emitting diodes (LED) have demonstrated data rates up to 5 Gb/s.[3] However, LED bandwidth is limited by the material carrier lifetime and efficiency is lowered when increasing the carrier density.[1] Laser-based VLC alleviates these problems and using laser diodes for free space VLC with non-return-to-zero on-off keying (NRZ-OOK) has shown data rates of up to 4 Gb/s.[4,5] Using multicarrier modulation schemes such as OFDM for laser-based VLC has achieved transmition speeds as high as 9 Gb/s.[6] Recently, a laser-based VLC system with a bandwidth of 3.5 GHz was demonstrated, with additional hardware for impedance matching and limited spectral efficiency 14 Gb/s was achieved.[7] Additionally, it is possible to combine different colour laser sources to increase data rates with wavelength division multiplexing (WDM) whilst providing standard white light illumination levels.[8] Recently, distributed feedback (DFB) lasers in GaN have been demonstrated making high channel density in WDM VLC systems possible.[9] Laser-based illumination has already been shown to produce high quality colour rendering for white light illumination using mutiple coloured sources and using phosphor colour converters.[10,11]

In this paper we surpass the highest data rate for single transmitter VLC using a GaN blue laser diode for free space transmission. 15 Gb/s over 15 cm using a commercial blue laser with a system 3 dB bandwidth of 1.4 GHz is demonstrated with a bit error rate (BER) below the forward error correction (FEC) limit. Successful transmission was also achieved over a distance of 197 cm at 13.5 Gb/s with a BER below the FEC limit.

The rest of the paper is organized as follows. In Section 2, the device characterization is presented. The OFDM modulation parameters are discussed in Section 3, experimental results are provided in Section 4 and conclusions are drawn in Section 5.

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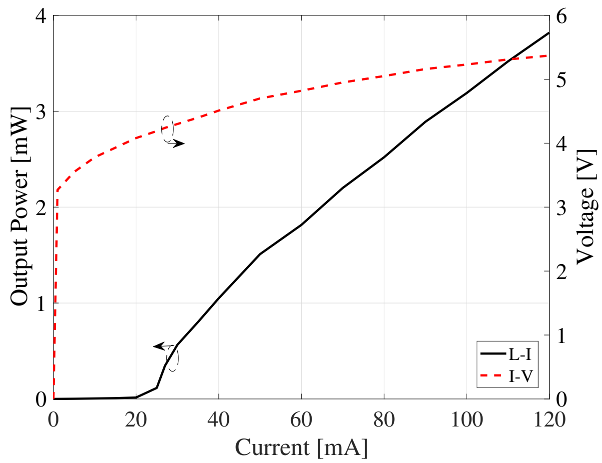

Figure 1. LVI characteristics of GaN laser at 17 ^oC.

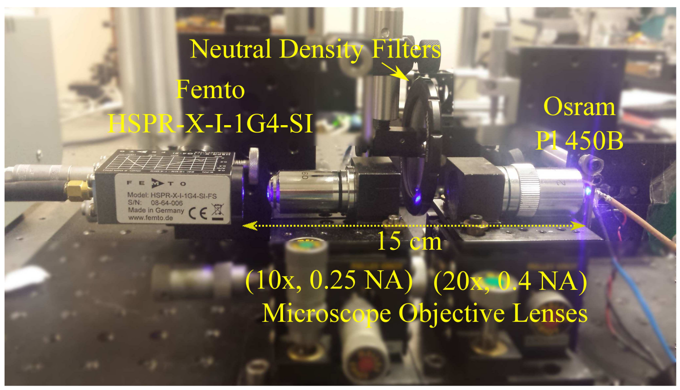

Figure 2. The optical system showing the laser, optical lens system and the photoreceiver.

2. DEVICE CHARACTERISATION

The laser diode used for transmission is OSRAMs PL450B device with a nominal emission wavelength of 450 nm. The luminance-voltage-current (LVI) characteristics of the device were experimentally obtained at 17 ^oC and are shown in Fig.1. The temperature was maintained with the use of a temperature controller (ILX Lightwave LDT-5910). The threshold current of the device is 25 mA at a turn-on voltage of 4.29 V. The laser diode output was collected and collimated with a microscope lens (0.40 NA, x20 magnification) before being transmitted over a free space link of 15 cm. It was then focused onto the power meter (Newport 1918-R) with a second microscope lens (0.25 NA, x10 magnification). The laser and lens setup are depicted in Fig.2. After surpassing the threshold, the power received at the power meter increased from 0.1 uW until a maximum reading of 3.82 mW.

The power meter was then replaced with a spectrometer (Ocean Optics USB 4000 Miniature Fibre Optic), whilst the lens configuration was maintained, and the wavelength of the laser light was measured at varying drive currents. The results are exhibited in Fig.3. The laser spectral width is around 2 nm and exhibited the typical Fabry-Perot red shift in wavelength with increasing current. The optical bandwidth and the frequency response were then measured using a network analyser (Agilent HP 8753ES).

A direct-current (DC) power supply and RF signal from the network analyser are combined via a bias-T and fed to the laser diode. After collecting and collimating as per LVI and Spectra measurements, the light is focussed onto the 0.4 mm effective active diameter of a high-speed silicon positive-intrinsic-negative (PIN) photoreceiver (Femto, HSA-X-S-1G4-SI), with a 3 dB bandwidth of 1.4 GHz, shown in Fig.2. The system frequency response at drive currents from 40 mA to 120 mA is shown in Fig.4. The maximum optical bandwidth of the system was

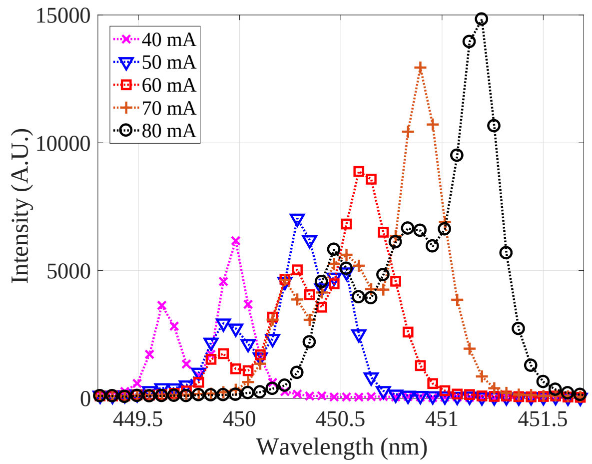

Figure 3. Spectra of the GaN laser at increasing drive currents.

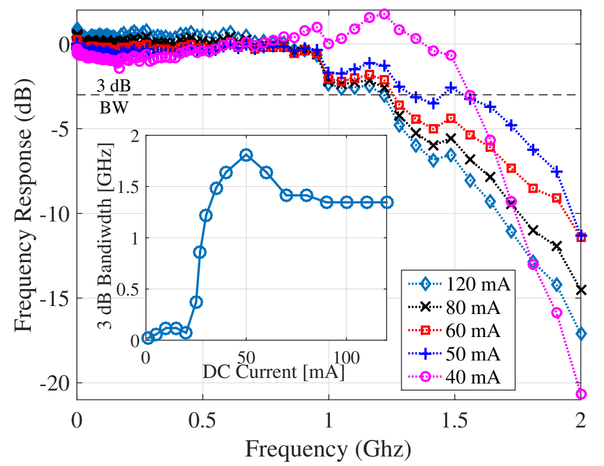

Figure 4. Frequency response at different drive currents. Inset shows 3 dB frequency at different drive currents.

found at a drive current of 50 mA shown in the inset of Fig.4. However, at higher drive currents where the laser bandwidth is expected to continue to increase, the system response is limited by the photoreceiver.

3. OFDM PARAMETERS

The OFDM waveform must be real and positive to utilize the intensity of the light source. To achieve this Hermitian symmetry must be imposed on the subcarriers.[12] The useful bandwidth of a system utilizing OFDM is limited to the positive frequency band therefore N_{FFT} subcarriers are evenly separated across the frequency range $-\frac{1}{2T_s}$ to $\frac{1}{2T_s}$ where T_s is the sampling period which corresponds to the Nyquist rate. The spectral efficiency of OFDM can be described as:[8]

$$\eta = \frac{\displaystyle\sum_{\substack{k=1 \\ M_k>0}}^{\frac{N_{\mathrm{FFT}}}{2}-1} \log_2 M_k}{N_{\mathrm{FFT}} + N\mathrm{CP}(1+\beta)} \ \text{bits/s/Hz}, \tag{1}$$

Where N_{FFT} is the number of subcarriers, M_k is the quadrature amplitude modulation (QAM) constellation size at the subcarrier k, N_{CP} is the length of the cyclic prefix (CP) and β is roll-off factor for the employed

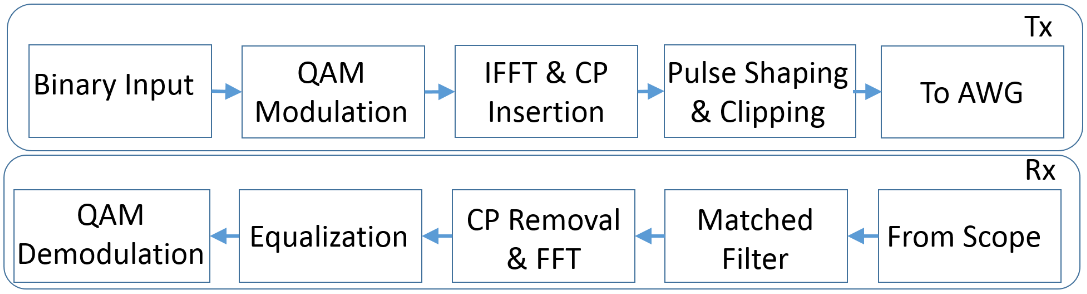

Figure 5. Block diagram showing OFDM transmitter and receiver components.

root-raised cosine (RRC) pulse shaping filter. The filter is chosen to satisfy bandwidth limitation and pulse duration requirements.

The number of subcarriers in the fast Fourier transformation (FFT), N_{FFT}, is equal to 1024 in this experiment. After exhaustive experimental measurements the cyclic prefix length, N_{CP}, was set to 5 which prevented any significant intersymbol interference (ISI). It is possible to use a bipolar OFDM signal to modulate a laser diode if a suitable DC bias is selected around which the signal will be centred. This is known as DC-biased optical OFDM (DCO-OFDM). The time domain OFDM signal has high peak to average power ratio (PAPR) which degrades the system performance due to non-linearities. Clipping of the time domain waveform is employed at marginal clipping noise distortion. In this experiment the upper and lower clipping was set as $+3\sigma$ and -3.5σ respectively. Where σ is the standard deviation of the time domain signal. Eqn.2 shows the square of σ given as:[8]

$$\sigma^2 = 2 \sum_{\substack{k=1 \\ M_k>0}}^{\frac{N_{\mathrm{FFT}}}{2}-1} \frac{E_{\mathrm{b}k} \log_2 M_k}{N_{\mathrm{FFT}}} \tag{2}$$

Where $E_{\mathrm{b}k}$ is defined as the electrical energy per bit on the k_{th} subcarrier. The OFDM transmitter and receiver are shown in the block diagram of Fig.5. The SNR from *a priori* estimation is used to determine the bit and energy allocation at each subcarrier. The binary data is encoded using M-QAM modulation before the inverse fast Fourier transformation (IFFT) converts the QAM symbols into the serial time domain waveform. The repition of the cyclic prefix helps the receiver mitigate any ISI effects, finally pulse shaping and waveform clipping alleviate ISI and nonlinearity distortion, respectively. The receiver then filters and removes the CP from the time domain waveform before the FFT converts it back to the frequency domain. Compensation of the effect from the channel is performed by equalization before QAM demodulation. The estimated SNR is used to adaptively load the subcarriers with bit and energy loading determined by the Levin-Campello algorithm.[13] Fig.6 shows the bit and energy loading of subcarriers and the channel capacity. The channel capacity is shown in Eqn.3 as described by Shannon:[14]

$$C = \log_2(1 + \frac{\alpha^2 E_{bk}}{\sigma_n^2/|H(k)|^2 + \sigma_d^2}) \tag{3}$$

Where α is a constant, σ_n^2 is the variance of the additive white Gaussian noise at the receiver, σ_d^2 is the frequency domain variance of the distortion noise and $|H(k)|^2$ is the channel gain at subcarrier k.

4. EXPERIMENTAL RESULTS

The OFDM signal is generated using MATLAB. The analog OFDM waveform is then produced using an arbitrary waveform generator (Tektronix AWG70001A), with a DC bias added via a bias-T and used to modulate the laser. The lens configuration is maintained from the device characterization stage described in Section 2 and a

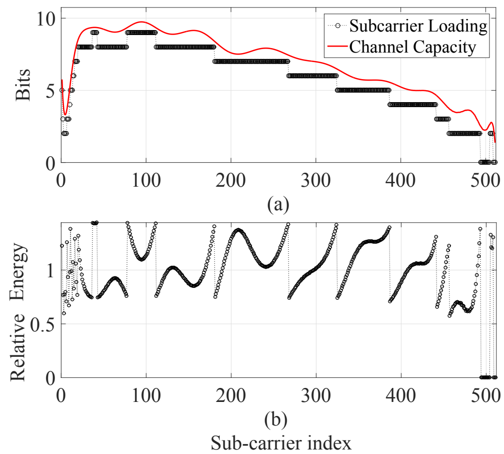

Figure 6. (a) The bit loading and channel capacity per subcarrier, both given in bits per subcarrier. (b) Energy loading per subcarrier.

FEMTO photoreceiver is placed at the receiver (HSPR-X-1G4-SI-FS). The output from the detector is fed to the oscilloscope (Tektronix MSO73304DX) and analyzed by MATLAB. Fig.7 shows the SNR over the 15 cm free space link at different drive currents. Data was transmitted using the optimal modulation voltage of 500 mV at varying drive currents and the MATLAB receiver code measured the end to end system SNR of each subcarrier. We can see that by increasing the drive current from 60 mA to 70 mA there is a noticeable improvement in the SNR of the high frequency subcarriers due to the increase in laser bandwidth with current. However, the inset in Fig.7 also details the reduction in SNR at lower subcarriers. We found 65 mA to be the optimum drive current at which the combination of increased high frequency SNR, and low frequency SNR reduction, resulted in the highest system data rate.

The channel performance was characterized as a function of channel attenuation. The optical power at the receiver was varied using a neutral density filter wheel. This varies the SNR and, therefore, the achievable data rate. Fig.8 shows the optical power required for different data rates whilst maintaining the BER below the FEC limit. This shows that the optical power can be reduced to 1 dBm and still transmit successfully at 14 Gb/s with the BER set below the FEC limit at $2.8 * 10^{-3}$. The data rate saturates at optical powers higher than 1 dBm and therefore it is possible to increase the transmission distance and maintain 14 Gb/s.

Fig.9 shows BER versus data rate for the 15 cm free space link. The black horizontal line illustrates the BER

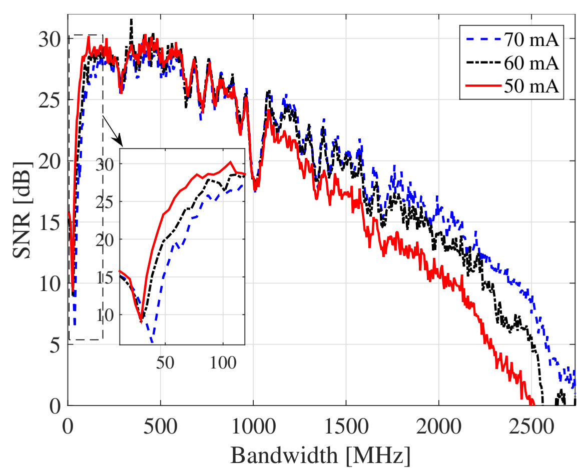

Figure 7. The SNR across the utilized bandwidth for different biasing levels.

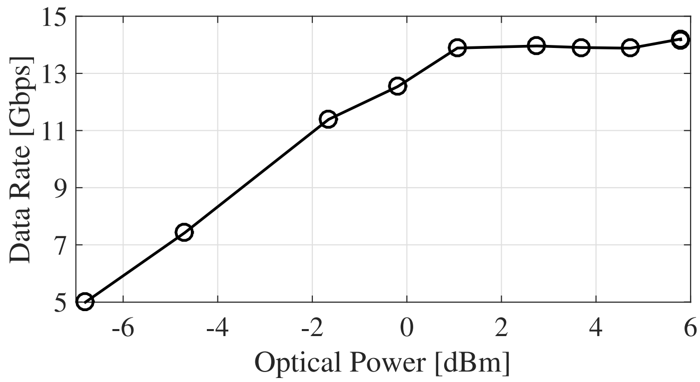

Figure 8. Data rate versus optical power over 15 cm link.

required to meet the FEC limit. From the figure it can be seen that 15 Gb/s data transmission can be achieved below the FEC limit. The transmission distance was then increased to 197 cm which was deemed a practical distance for dual purpose lighting VLC systems or remotely operated underwater vehicles. The receiver lens, previously a microscope lens, was replaced by a larger aspheric lens (Thorlabs ACL7560U-A). The laser bias and modulation voltage were unchanged. The maximum successful data rate is reduced to 13.5 Gb/s as shown in Fig.9 due to the increased losses and therefore decreased SNR. The relatively small decrease in maximum bit rate for this distance is due to the use of a near collimated laser output and the fact that the maximum bit rate at 15 cm was invariant with receiver powers between 1 dBm and 6 dBm.

5. CONCLUSIONS

The high bandwidth and high data rate capabilities of the OSRAM PL450B laser in the context of a VLC transmission system have been demonstrated. With a system 3dB bandwidth of 1.4 GHz, record data transmission system capacity has been demonstrated with data transmission over a 15 cm free space link at 15 Gb/s. This has been achieved through high system SNR and adaptive bit loading. The optical power required for achieving 14 Gb/s over the 15 cm link was found to be 1 dBm. Over a 197 cm free space link, successful transmission was achieved at 13.5 Gb/s. Given the system is currently limited by the photoreceiver bandwidth, we believe that the overall system bandwidth could be improved without sacrificing spectral efficiency as long as the SNR of the detected signal is maintained.

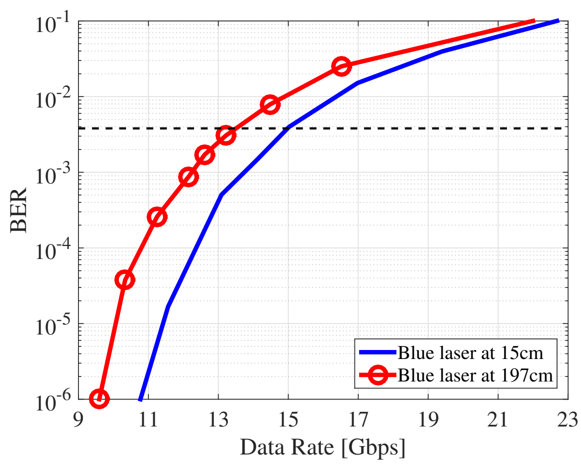

Figure 9. Data rate versus BER over 15 cm and 197cm link.

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Shaun Viola and Mohamed Sufyan Islim contributed equally to this work.

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